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Modeling of Compressible Turbulent Shear Flows

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1. Motivation and Objectives

Despite all the recent development in computer technologies and numerical algorithms, full numerical simulations of turbulent flows are feasible only at moderate Reynolds numbers and for flows with relative simple geometries. Turbulence models provide alternatives in the pressing need for the prediction of turbulent flows and,in fact, have become an important pacing factor for the successful development of computational fluid dynamics (CFD). With the advent of supercomputers, however, it has become more affordable to apply second order closure models in the prediction of flows with complex effects; such as strong curvature, three-dimensionality and compressibility. The main goal of this research is to develop new second order moment closures for compressible turbulence. It has been shown that the models based on the extension of those developed originally for incompressible flows fail to predict adequately turbulent flows at high Mach numbers. In this attempt, the compressibility effects will be explicitly considered. A successful development of these models that take into account directly the compressibility effects may have a range of technological implications in the design of supersonic and hypersonic vehicles.

2. Work Accomplished

During this early stage of the task, the goal is to obtain an objective yet comprehensive understanding of the development and the current status of compressible turbulence modeling. Due to the variable density effects in compressible flows, density correlation terms appear in the governing equations for the mean flow, if the conventional ensemble averaging technique is applied. These terms do not exist in incompressible flows and need to be modeled. On the other hand, the mass-weighted-averaging or Favre procedure generates a set of mean equations that have the similar forms as they are for incompressible flows. One may then incline to use the incompressible analog in compressible flow calculations. A simple test, however, should show that a direct application of the exact incompressible models fails. One of the main effects that is excluded in incompressible models is the finite propagation speed of disturbances. In compressible flows, modulation of flow properties occurs only within Mach cones of influence, with acoustic time delay. This introduces additional scales for the transport properties. Caution also needs to be exercised in comparing Favre-averaged calculations with experiments, since the differences between Favre-averaged and measured quantities may not be negligible at high Mach numbers.

Compressible turbulence modeling is still in its infancy. This appears to be true both theoretically and computationally. Recently, a new concept called dilatation dissipation was proposed. Dilatation dissipation, as opposed to the solenoidal dissipation in incompressible flows, accounts for the viscous dissipation of turbulent kinetic energy due to volume fluctuations. Models accommodating this effect show the importance of this additional drain of turbulent kinetic energy in order to obtain adequate model predictions. Dilatation dissipation appears to be among the direct consequencies of compressibility effects.

Another school of thought on compressibility effects focuses on the changes of turbulence structures at high Mach numbers. Note that these structures are identified by using conditional sampling techniques in experiments. Due to the communicability problem between interacting elements, structures that are highly efficient in extracting energy from the mean flow at low Mach numbers no longer prevail as the Mach number increases. They are replaced by structures that are less sensitive to the Mach number. This selective amplifying behavior is describable by quasi-linear theory, which view the turbulence energetics as physical manifestations of ongoing nonlinear instability in turbulent shear flows.

The above mentioned matters are described in detail in an ICOMP/ CMOTT report [1] that is in preparation. Equations for the second order moments and the mean flow as a result of the application of different averages will also be given. Modeling methodologies used in compressible flow calculations will be reviewed. The evaluation process performed during the present stage of the research has identified avenues that will be pursued during the next period of this task.

3. Future Plans

(1) Develop second order models for compressible turbulence based on ensemble averages. This may be assisted by first developing $k-\epsilon$ types of models to identify important mechanisms.

(2) Develop unconventional models that incorporate explicitly the characteristics of the structures of compressible turbulence.

The developed models will be applied to certain benchmark flows with and/or without chemical reactions.

4. Publications

1. Liou, W. W. and Shih, T.-H., "On the Basic Equations for the Second-order Modeling of Compressible Turbulence," CMOTT-91-06, 1991.
2. Liou, W. W. and Morris, P. J., "An Comparison of Numerical Methods for the Rayleigh Equation in Unbounded Domains," CMOTT-91-05, 1991.